REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
06 Jun 1996

3. REPORT TYPE AND DATES COVERED
Summary 01 Jun 1996 - 31 May 1997

4. TITLE AND SUBTITLE
Stack/Heat-Exchanger Research
for Thermoacoustic Heat Engines

5. FUNDING NUMBERS
PE 61153N
G N00014-97-1-0008

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
ONR 331
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release:
Distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The goal of this project is to develop novel configurations of heat pumping elements and heat exchangers for thermoacoustic heat engines. The approach will be to use anisotropic systems employing innovative technology. This approach will allow a heat exchange fluid to flow directly across the heat pumping element of the thermoacoustic heat engine (the "stack"), eliminating the necessity of separate heat exchangers and possibly improving efficiency. During the past year a radically new design, which is robust (using only stainless steel and epoxy), relatively easy to fabricate, and employs a filament array or "pin" stack, has been developed. The pin-stack elements are being made commercially, and other parts have been fabricated for testing the system in the "Space Thermoacoustic Refrigerator" of S. L. Garrett.

14. SUBJECT TERMS

Acoustics, Thermodynamics, Heat Engine, Refrigerator

15. NUMBER OF PAGES
6

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

NSN 7540-01-280-5500

DTIC QUALITY INSPECTED 3

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

STACK/HEAT-EXCHANGER RESEARCH FOR THERMOACOUSTIC HEAT ENGINES

This annual summary report presents the accomplishments for ONR grant N00014-97-1-0008,"Stack/heat-exchanger research for thermoacoustic heat engines". The goal is to eliminate the necessity of separate heat exchangers at the ends of the heat pumping element (the "stack") of a thermoacoustic heat engine, thereby improving efficiency and simplifying the fabrication of the engine. Of particular interest is the application to a thermoacoustic refrigerator (TAR). The approach will be to use an innovative filament array or "pin" stack together with a transverse array of stainless steel capillaries to form an anisotropic stack/heat-exchanger (ASHE). In this approach the oscillatory flow of the thermoacoustic fluid in one direction is combined with the flow of a heat exchange fluid in a perpendicular direction. The pin-stack elements are being made commercially, and other parts have been fabricated for testing the system in the existing "Space Thermoacoustic Refrigerator" (STAR) of S. L. Garrett.

General developments

The Ph.D. candidate in Physics, David Zhang, continues to grow in laboratory skills, and is an excellent student in regard to innovation, independence, and industry. The new design for the ASHE was developed through his efforts. As discussed below, a key element of the design (ridges running the length of thin stack plates which provide rigidity and spacing) were Zhang's innovation. A nontrivial task accomplished by Zhang was to find a company which could fabricate the pin-stack plates. Zhang also designed the adaptor for testing the new ASHE unit in the STAR hardware completely on his own.

For the Penn State University Graduate Research Exhibition, Zhang demonstrated a small TAR using a hi-fi speaker, a plexiglas resonator, and a stack instrumented with thermocouples. Attendees could press a button and watch the temperature drop. Zhang's exhibit was featured in two local newspaper articles.

Because of the proprietary nature of this research, no papers have been submitted for publication. A patent disclosure for the new ASHE design has been submitted.

Background

A major contributor to the depletion of the earth's ozone layer is the reaction of the ozone with chlorofluorocarbons (CFC's) which are released into the earth's atmosphere from refrigerators which leak CFC's. In order to satisfy current and anticipated regulations governing the use of CFC's, it will be necessary to develop new types of refrigerators which do not use CFC's. A promising technology involves the thermoacoustic effect, in which the oscillatory motion of a gas in an acoustic field is coupled to a temperature gradient at a solid surface parallel to the motion. Reviews of this effect and its application in refrigerators and other heat engines (some nearing commercialization), are available in the literature.[1,2]

In order to increase the heat carrying capacity of the thermoacoustic heat engine, a large number of solid surfaces are used in a parallel configuration, as in a stack of plates, a spiraling sheet, an array of capillaries, or an array of filaments or "pins"; this part of the thermoacoustic heat engine is referred to as the "stack". At each end of the stack are heat exchangers which would connect the refrigerator to an ambient temperature reservoir and to the load to be cooled. The sealed acoustic resonator is filled with a non-CFC gas, such as a helium-argon mixture. It should be noted that the spacing of the surfaces in the stack (or the inside diameter of capillaries in an array) is on the order of the thermal penetration depth for the gas, typically a few hundred microns.

Key elements in a high power thermoacoustic refrigerator are the heat exchangers at the ends of the stack. For an isothermal heat-exchanger, the length of the exchanger (in the direction of the gas particle velocity) should be on the order of the gas particle peak-to-peak displacement (as large as several millimeters). A difficulty arises from the disparity in the length scales between the stack (with a scale of several hundred microns) and the heat exchanger pipes (with a scale of several mm). The TAR could be improved if the heat-exchanger were incorporated into the stack with a matching length scale. This would form an anisotropic stack/heat-exchanger (ASHE) unit, which could transport large heat flows laterally (across the stack) but not longitudinally (along the stack). If such a heat-exchanger used a flowing fluid, rather than heat conduction, to transport the heat, then one could not only handle higher heat loads, but one could also have graded exchanges with the external heat exchangers. That is, the temperature of the heat-exchanger fluid entering and exiting the external heat-exchanger could be made to match the temperature at the point of entry or exit of the exchanger in the stack.

The New Design for the Anisotropic Stack/Heat-exchanger Unit

The new design for the ASHE is shown in Fig. 1. For simplicity the prototype unit has a square cross section. [In Fig. 1, lengths are not drawn to scale.] In this design the stack is a "pin-stack", consisting of a stack of plates, one of which is shown schematically in Figs. 1a and 1b. Each plate is fabricated from a thin (0.05 mm) stainless steel sheet; elongated openings (of width 0.25 mm) are chemically etched in the plate resulting in an array of square cross-section (0.05 x 0.05 mm) pins. Wide sections across the plate provide additional support for the pin array. As shown to the right in Fig. 1a and in Fig. 1b, ridges of height 0.30 mm are pressed into the plate along its length. These ridges provide longitudinal rigidity as well as spacing between the plates when stacked; the ridges are asymmetric across the plate, so that when the plates are stacked with alternating orientations, the ridges alternate in position, as may be seen in Fig. 1c. Assembly of the ASHE is illustrated in Fig. 1c, which shows the pin-stack plates with thin-walled stainless steel tubes (of 0.60 mm overall diameter, 0.025 mm wall thickness) for carrying the heat-exchanger fluid running laterally across the plates. The lateral heat-exchanger tubes and the longitudinal pins comprise the orthogonal basis of the anisotropic stack/heat-exchanger.

Assembly of the ASHE unit is facilitated with the frame shown in Fig. 1d. The assembly

process involves placing a layer of tubes in one pair of slots across the frame, along with two plates at the same level, which extend beyond the other pair of slots. Next, a layer of tubes are placed across the second pair of slots, along with two plates at this level. The results may be understood by imagining Fig. 1c lowered into the frame in Fig 1d. The assembly process is repeated until the frame is filled. At each level, the ends of the tubes are coated with epoxy to facilitate sealing with the frame, i.e. isolating the inside of the heat-exchanger tubes from the stack region inside the frame. After the frame is filled, the top is sealed with a plate and epoxy, and heat-exchanger fluid manifolds are epoxied at the slots.

In the illustrated ASHE, the acoustic gas oscillates through the openings between the heat-exchanger tubes (as may be seen in Fig. 1c) and longitudinally along the pins in the stack plates; the heat-exchanger fluid flows at right angles through the tubes. The heat to or from the acoustic gas near the ends of the stack conducts through the thin walls of the tubes, and is transported by the heat-exchange fluid.

Test of the Anisotropic Stack/Heat-exchanger in the STAR Refrigerator

In order to test the new ASHE, an existing, modular TAR, the Space Thermoacoustic Refrigerator (STAR) developed by T. J. Hofler, S. L. Garret, and others at the Naval Postgraduate School in Monterey, CA, will be used. This TAR is fully instrumented and well characterized, and thus will provide a means of obtaining meaningful data quickly. It is about 10 cm in diameter and about 45 cm in length; it has been used to provide 6 W of cooling power with an efficiency, relative to Carnot, of about 10%.

In order to test the new ASHE in the STAR apparatus, the existing stack and one of the STAR heat exchangers is removed. Because the new ASHE uses a flowing heat-exchanger fluid, while the existing STAR uses conduction through copper components, an adapter flange with fluid transport channels had to be developed. The adapter is shown in Fig. 2a, and its installation into the STAR apparatus is shown in Fig. 2b. The fluid transport channel on one side of the flange is shown with dotted lines in Fig. 2; the channel connects a port on the side of the flange to a manifold sealed over the open ends of the heat-exchanger tubes discussed with Fig. 1. Not shown in Fig. 2 is the existing STAR acoustic driver, which bolts onto the open end of the adapter.

Upon arrival of the commercially fabricated pin-stack plates, assembly of the ASHE should be straightforward, and testing with the STAR apparatus may commence.

Current and Other Funding

Other research grants include:

1. ONR, Physics Division, N00014-92-J-1186, November 1, 1991 to October 31, 1994, 300,000/3 yr, “Innovative acoustic techniques for studying new materials and new developments in solid state physics”; includes 1 man-month of time for the principle investigator.

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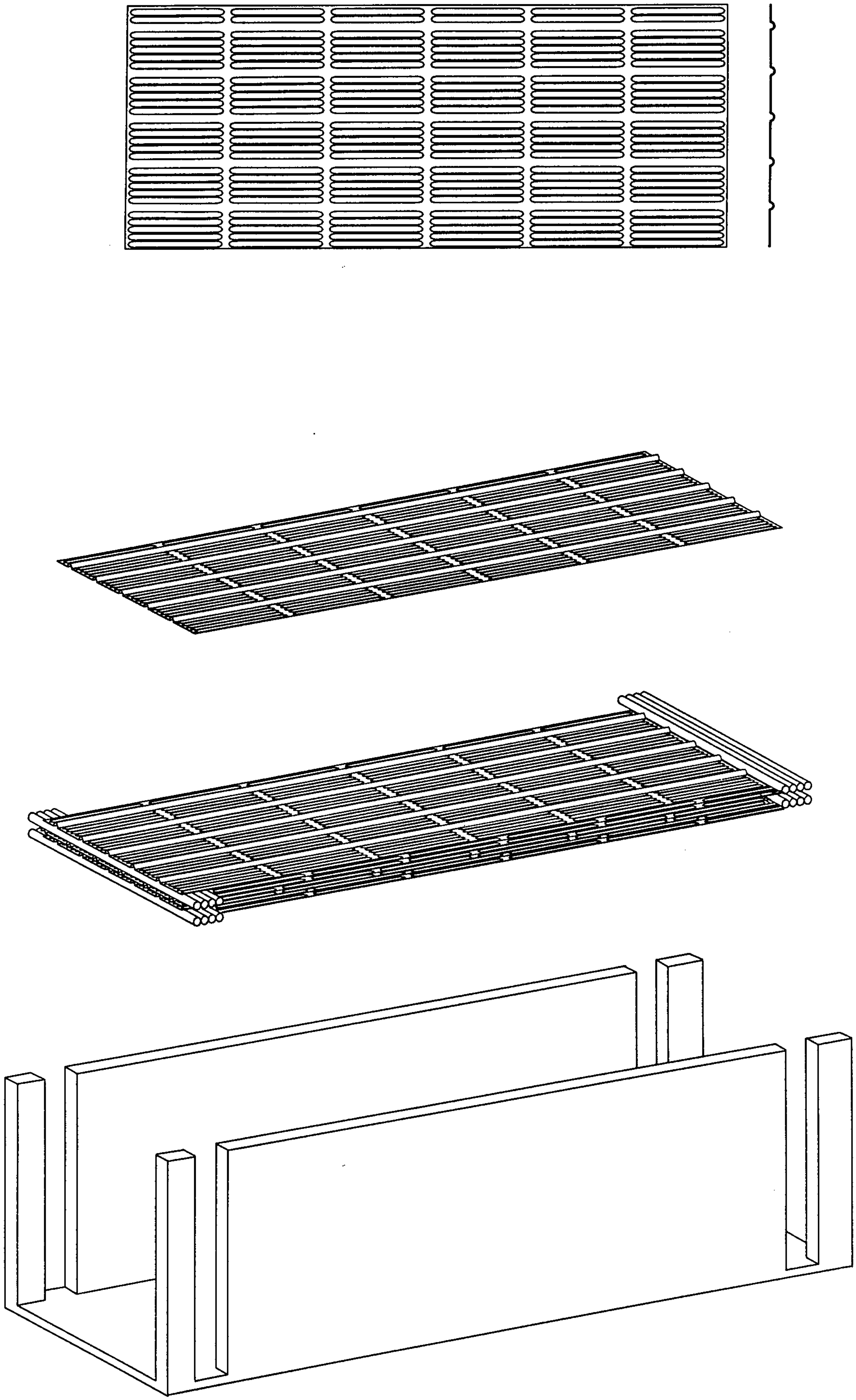
1. G. W. Swift, J. Acoust. Soc. Am. **84**, 1145 (1988). Thermoacoustic engines.

2. G. W. Swift, *Physics Today* , July 1995, p. 22.



(a)

(b)

(c)

(d)

Fig. 1

(a)

(b)

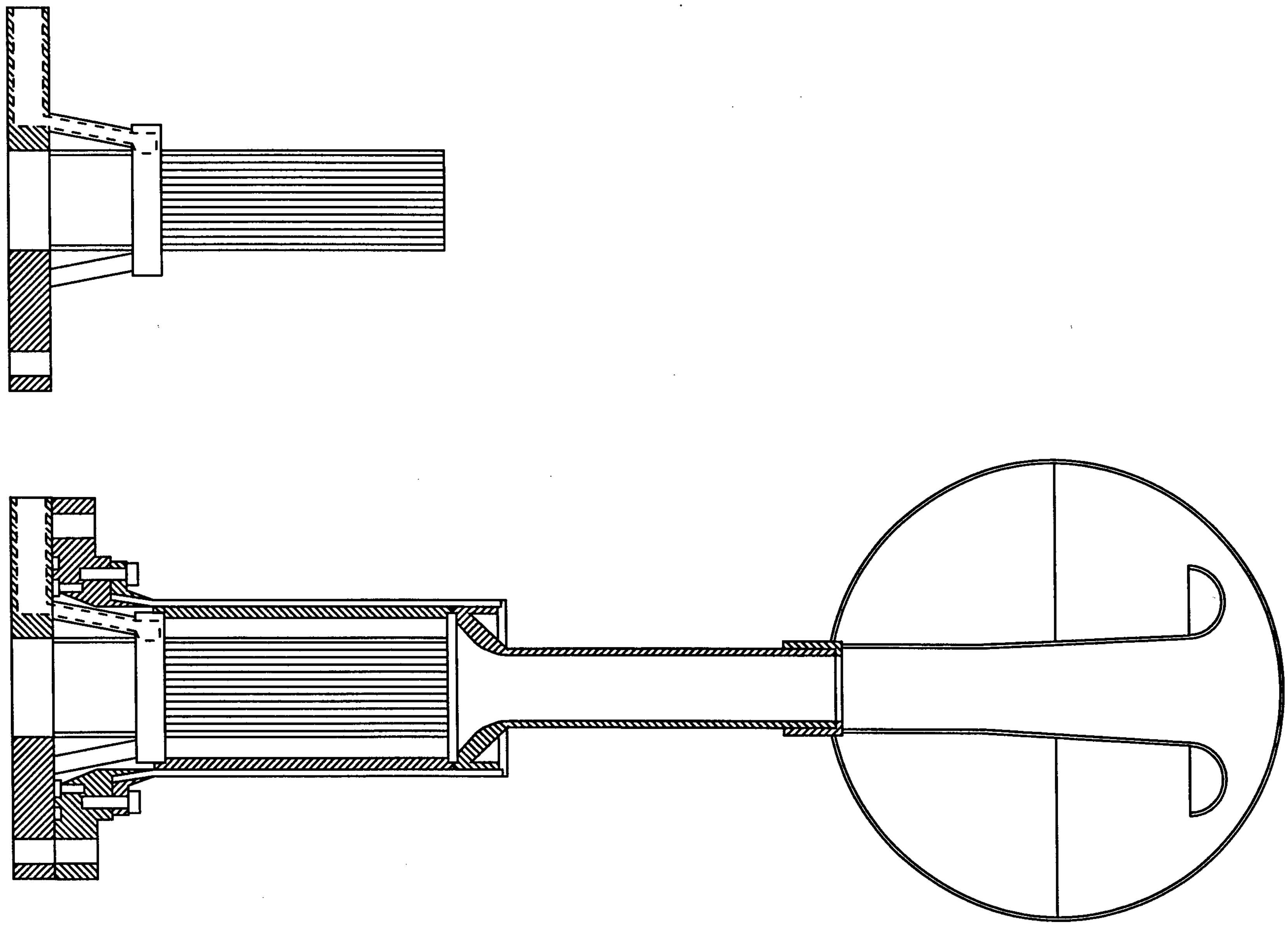


Fig 2.

OFFICE OF NAVAL RESEARCH
PUBLICATIONS / PATENTS / PRESENTATIONS / HONORS REPORT
for
01 JUNE 1996 through 31 MAY 1997

Contract/Grant Number:	N00014-92-J-1186/N00014-97-1-0008
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a. Number of papers submitted to refereed journals but not yet published:	1
b. Number of papers published in refereed journals:	3
c. Number of books or chapters submitted but not yet published:	0
d. Number of books or chapters published:	2
e. Number of printed technical reports & non-refereed papers:	1
f. Number of patents filed:	1
g. Number of patents granted:	0
h. Number of invited presentations at workshops or prof. soc. meetings:	8
i. Number of contributed presentations at workshops or prof. soc. meetings:	4
j. Honors/awards/prizes for contract/grant employees:	0
k. Number of graduate students supported at least 25% this year:	4
l. Number of post docs supported at least 25% this year:	2

Grad Students FEMALE:	0	Post-Docs FEMALE:	1
Grad Student MINORITY:	0	Post_Docs MINORITY:	0
Grad Student ASIAN E/N:	1	Post-Docs ASIAN E/N:	1
Undergrad FEMALE:	2		

PUBLICATIONS, PRESENTATIONS, ETC.

PAPERS SUBMITTED TO REFEREED JOURNALS BUT NOT YET PUBLISHED

J. D. Maynard, "Wave propagation in periodic, random, and quasiperiodic media, with a tutorial on Anderson localization" submitted as a Tutorial Review to J. Acoust. Soc. Am., June, 1997

PAPERS PUBLISHED IN REFEREED JOURNALS

1. T. Zhang, B. Bennett, V. A. Hopkins, and J. D. Maynard, "Effects of finite amplitude fields on superfluidity", Proc. 21st Intl. Conf. Low Temp. Phys., Czech. J. Phys. **46**, 145 (1996).
2. T. Zhang, B. Bennett, V. A. Hopkins, and J. D. Maynard, "Using liquid helium to study fluid interface coalescence effects", Proc. 21st Intl. Conf. Low Temp. Phys., Czech. J. Phys. **46**, 377 (1996).
3. P. S. Spoor, J. D. Maynard, M. J. Pan, D. J. Green, J. R. Hellman, and T. Tanaka, "Elastic constants and crystal anisotropy of titanium diboride", Appl. Phys. Lett. **70**, 1959-1961 (1997).

BOOKS OR CHAPTERS PUBLISHED

1. J. D. Maynard, "Phonons in Crystals, Quasicrystals, and Anderson Localization", in *Encyclopedia of Acoustics* , ed. M. J. Crocker (John Wiley and Sons, New York, 1997), pp 651-660.
2. J. D. Maynard, "Acoustic Holography", in *Encyclopedia of Acoustics* , ed. M. J. Crocker (John Wiley and Sons, New York, 1997), pp 1281-1290.

PRINTED TECHNICAL REPORTS AND NON-REFEREED PAPERS

Philip S. Spoor, Physics Ph.D. Thesis, 1997; *Elastic Properties of Novel Materials using PVDF Film and Resonant Ultrasound Spectroscopy*

PATENTS/APPLICATIONS

Patent Disclosure, "Anisotropic stack/heat-exchangers for thermoacoustic heat engines" (Upgraded version, June, 1997).

INVITED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

1. Lecture Series, 1996 Physical Acoustics Summer School, Asilomar Conference Center, Pacific Grove, CA, June 21-28, 1996. Host: Henry E. Bass. "Periodic, random, and quasiperiodic media"
2. Lecture Series, UCLA Nonlinear Science Summer School, Los Angeles, CA, June 28-29, 1996. Host: G. A. Williams, "Anderson localization of nonlinear waves"
3. Thermoacoustics Review Meeting, Asilomar Conference Center, Pacific Grove, CA, November 13-15, 1996 "Anisotropic heat-exchanger/stack configurations for thermoacoustic heat engines"
4. Plenary Lecture, XXIII Internation Meeting on Acoustical Imaging, Boston, MA, April 13-16, 1997. "Acoustic Imaging of Active Sources" Chairperson: Sidney Lees. 57 Park Plaza Hotel
5. Resonance Meeting, Asilomar Conference Center, Pacific Grove, CA, May 11-15, 1997. "Determining the radiation impedance for arbitrarily shaped surfaces"
6. Resonance Meeting, Asilomar Conference Center, Pacific Grove, CA, May 11-15, 1997. "Resonant photoacoustic spectroscopy of optical materials"
7. University of Toronto, Department of Physics, Toronto, CANADA, September 12, 1996 Host: Steve Morris "Tuning-up a quasicrystal"
8. University of Maryland, Department of Physics, College Park, MD 20742-4111. April 22, 1997 Host: J. Robert Anderson "Tuning-up a quasicrystal"

CONTRIBUTED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

1. B. Bennett, T. Zhang, V. Hopkins, and J. D. Maynard, "Using liquid helium to study fluid interface coalescence effects", APS Division of Fluid Dynamics, 49th Annual Meeting, Syracuse University, Syracuse, NY 13244, November 23-26, 1996
2. D. C. Zhang and J. D. Maynard, "High power, high efficiency drives for annular thermoacoustic refrigerators", J. Acoust. Soc. Am. **100**, 2816 (1996). December 2-6, 1996. Sheraton-Waikiki Hotel, Honolulu, HI
3. L. C. Krysac and J. D. Maynard, "Statistical and deterministic dynamics during fracture of brittle corbon foam", Bull. Am. Phys. Soc. **42**, 460 (1997). Kansas City, MO
4. B. Bennett, V. Hopkins, T. Zhang, and J. D. Maynard, "Studies of liquid interface impact using helium", Bull. Am. Phys. Soc. **42**, 615 (1997). Kansas City, MO
5. P. J. White and J. D. Maynard, "Thin film characterization using resonance ultrasound spectroscopy", Resonance Meeting, Asilomar Conference Center, Pacific Grove, CA, May 11-15, 1997.

GRADUATE STUDENTS SUPPORTED AT LEAST 25%

1. Philip Spoor (Ph.D. candidate, acoustics) began Fall 1989, Elastic Constant Measurements for Quasicrystals
2. Brian Bennett (Ph.D. Candidate, Acoustics Program) began summer 1994, Fluid coalescence
3. David Chao Zhang (Ph.D. candidate, physics) began summer 1994, Thermoacoustic heat engines
4. Jason White (Ph.D. candidate, physics) began summer 1994, Resonant Ultrasound Spectroscopy

POSTDOCTORALS SUPPORTED AT LEAST 25%

1. Tian-ming Zhang, Postdoctoral Scholar, 1994-1996
2. Cindy Krysac, Postdoctoral Scholar, began July, 1994

MISCELLANEOUS

Undergraduates Involved in Research:

1. Joseph Buck, Senior, 1994-96
2. John Lelii, NSF Research Experience for Undergrad. student 1995-96
3. Patrick Johnston, 1994-96
4. Christina D'Arrigo, WISER student, 1996,97
5. Ivonne D'Amato, WISER student, 1996,97
6. Bill Siddall (REU student), 1997